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**General Technical
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Advancing Toward Closed Forest Ecosystem Models: Report on a Workshop

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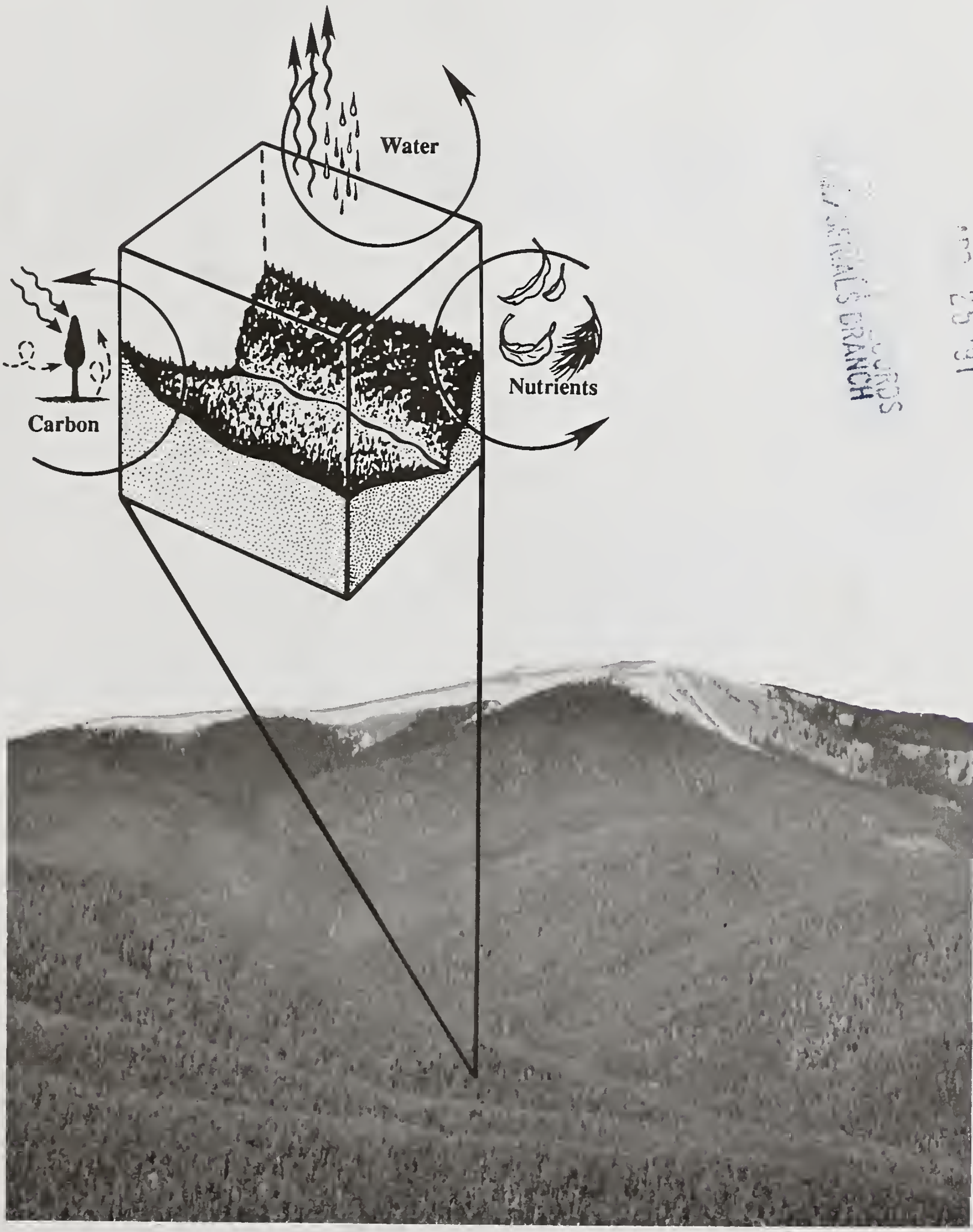

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Advancing Toward Closed Forest Ecosystem Models: Report on a Workshop

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Abstract

Scientists attending a workshop addressed the status of developing closed forest ecosystem models in which all important fluxes and pools are understood and parameterized. They concluded that major gaps exist in modelling the carbon cycle, particularly regarding carbon fixation by forest stands and the allocation of carbon after it has been fixed, and important gaps also exist in nutrient cycling. The hydrologic cycle is understood best of the three cycles examined, but data are still limited. The testing of models operating at similar spatial and temporal scales and the integration of models operating at different scales were identified as important areas requiring research.

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Advancing Toward Closed Forest Ecosystem Models: Report on a Workshop

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Introduction

Research on forest ecosystems is becoming more crucial than ever before. The issue of climate change raises considerable uncertainty about the role of forested ecosystems in regulating the global atmospheric balance of CO_2, particularly in the northern hemisphere (Tans et al. 1990). In forest management, a dramatic shift is occurring in the United States and elsewhere toward management of forests as ecosystems rather than simply as commodity-oriented production systems.

To learn how ecosystems function, we must be able to measure or estimate inputs and outputs of materials and to describe the processes involved in the regulation and behavior of the ecosystems. We also must be able to simulate these processes and their results at various spatial and temporal scales. However, significant gaps exist in our knowledge of the inputs, outputs, and interactive mediative processes of forest ecosystems. Much research has focused on individual cycles of material flux—the carbon, nutrient, and hydrologic cycles—and too little attention has been paid to quantifying all the cycle components and the key processes or to examining the interactions among the cycles.

A workshop concerned with various aspects of forest ecosystem modelling was held in Colorado in June 1990. This report summarizes the aims of the workshop and its findings. The aims were:

- to assess our state of knowledge about the carbon, water, and nutrient cycles of temperate forest ecosystems, at the level of the trees and stands.
- to identify those areas where knowledge can be considered adequate and those on which research should be concentrated. Some assessment of the adequacy of current research technology was to be included.
- to evaluate the feasibility of developing closed system models of the carbon, water, and nutrient cycles, either alone or including all factors.

The workshop was concerned with closed models describing the flows of carbon, water, and nutrients through forest stands. A closed system model may be defined as a mathematical model of a system with specified boundaries in which all the flows into and out of the system are accounted for. It is, of course, possible to write models that are closed in algebraic terms; i.e., the calculations appear to account for the flows and storage of all material. The problem is whether the data needed to establish the parameter values for all the equations are available. Thus one aim of the workshop was to consider the experiments and observations needed for the development of models in which closure does not depend on uncertain residual terms, but is achieved through full knowledge of all fluxes and stores in the system. The level of system organization chosen for consideration was the stand, but discussions also addressed levels from individual tree branches to entire regions.

The term "closed system model" implies that the models are process-based or phenomenological—they are based, for example, upon the processes involved in tree growth. There was general agreement on the need for this type of model. Conventional forest production models are derived from measurements of trees in the field and statistical descriptions of their size distribution and the changes in size over time. The problem with this approach is its narrow scope and lack of flexibility. Such models are completely empirical and site-specific—they are essentially descriptions of tree growth rates (often simply merchantable volume) on particular sites subjected to a particular range of weather conditions. They cannot be used to examine the consequences of any significant departure from the conditions pertaining over the period of the measurements, particularly changes such as increases in atmospheric CO_2 or temperature or changes in water regimes. Even the consequences of changes in tree populations can only be simulated if empirical relationships between tree growth patterns and populations have been established. Nor can such models be used to examine a wide variety of ecological and physiological processes affecting the health and behavior of forest ecosystems.

Process-based models reflect the influence of external factors on tree growth through their effects on physiological processes that contribute to growth, and they may be formulated to describe other relevant processes such as nutrient cycling. While process models may appear quite empirical when viewed from lower scales, they focus on a representation of the basic functioning of the system under consideration. In principle they can be written in completely general forms. Such models may serve chiefly to guide further research, or they may enable managers to evaluate the probable outcome of various alternative courses of management action or of events such as a heavy insect attack. They also can provide the means for policy-makers to examine the likely consequences of factors such as climate change or pollution on forests at levels ranging from the local to the global. The need for closed system models, in which all the flows of matter are accounted for, and for different kinds of models, emerges clearly from such considerations.

Organization of the Workshop

About 40 scientists concerned with various aspects of forest ecology and productivity met from June 10 to June 15, 1990, in the Colorado Rocky Mountains. The authors of this report organized the workshop, which was held near Granby, Colorado. The workshop was supported by the USDA Forest Service, the National Science Foundation, and the Electric Power Research Institute. The 40 participants (list attached) included scientists from Australia, New Zealand, and the United Kingdom; U.S. representatives were from the USDA Forest Service and from research centers and universities.

The workshop included a field trip to the Fraser Experimental Forest, established in 1937, to examine experiments in watershed hydrology and tree growth. The Fraser Experimental Forest is part of the Rocky Mountain Forest and Range Experiment Station. Work there includes studies of forest effects on water and nutrient balances, summer and winter components of evapotranspiration from forests, the effects of stand density on tree growth, measurements of respiration, studies on foliage dynamics, and factors affecting the vigor of old trees.

An outline of the discussions and the main conclusions from the meeting are provided in this report. A somewhat novel procedure was adopted for six keynote papers. Two papers dealt with aspects of the carbon balance of forest stands and trees, two with nutrients, and two with hydrology. Each of these papers was presented by a pair of scientists chosen for their expertise in the area. The presenters did not necessarily work together, or even know each other. They were asked to liaise with one another and to bring to the workshop only draft manuscripts, with the intention of developing the final versions after discussions at the meeting. The first phase of this approach clearly worked out well; the success of the second phase—final joint manuscripts reflecting discussion at the meeting and the authors' points of view—remains to be seen. The journal *Tree Physiology* has agreed to publish the proceedings of the meeting as a special issue; we expect this to come out in 1991.

Following the presentation of the keynote papers, discussion sessions considered the state of our knowledge about the carbon, water, and nutrient cycles of forests. The discussion session leaders were charged with identifying the requirements, in terms of theoretical knowledge and empirical information, for a mechanistic model of carbon, water, or nutrient cycling in a forest stand. The timeframe was to be a year, which implied **not** a calculation time step of a year, but rather that it should be possible to close the system (balance the inputs and outputs) over a year. The discussion groups also were asked to consider the measurements and technology needed to fill the gaps in knowledge and information identified in the discussions. Discussion session leaders reported back to a plenary session of the meeting.

Results of Topical Discussion Sessions

Carbon.—The group concerned with carbon listed the key processes in the carbon cycle and ranked them in order of the urgency of our current needs for information about those processes. The critical knowledge gaps include:

- carbon allocation (data and research on processes),
- respiration,
- belowground biomass (a facet of allocation),
- photosynthesis (carbon gain),
- foliage dynamics (again a facet of carbon allocation),
- decomposition and herbivory, and
- organ turnover and organism mortality.

Clearly the fate of carbon fixed in photosynthesis, along with the total carbon balance of stands, are major gaps in our knowledge of carbon cycling in forest ecosystems.

Water.—The consensus regarding the hydrologic cycle was that our ability to account for all the flows is reasonably good. However, the scale at which the system is being examined affects our capacity to deal with it. For the hydrologic cycle, there are differences in approach if the answers required pertain to water flow from a catchment or to the calculation of the soil water content under a stand of trees. Discussions ranged from a consideration of our capacity to make appropriate and accurate measurements of rainfall and snowfall, through the problems of estimating canopy interception and evaporative losses, to the assessment of transpiration. The discussion group listed the main processes of concern as:

- interception,
- transpiration (including transpiration from the understory),
- evaporation (including losses from the litter layer, the soil and snowpack), and
- the routes followed by flow through the soil and trees.

Despite the background of many years of research on transpiration, interception, and radiant energy absorption, the group still listed these as areas where knowledge needs improving. The need for good information about canopy dynamics also was noted by the discussion group concerned with water. Discussions on the hydrologic cycle also identified a problem that reemerged throughout the meeting—the question of stand heterogeneity and how to handle it.

Nutrients.—Discussions about nutrition focused on established rates of nutrient cycling, how well they are known, and the adequacy of the methodologies available for measuring them. The group concluded that large gaps exist in three key components of the nitrogen cycle:

- mineralization rates,
- microbial processing of inorganic pools, and
- the input of nitrogen into forest systems from decomposition of belowground detritus.

Current understanding of nitrogen cycling in temperate forests is ahead that of phosphorus, partly because of the added complications in phosphorus cycling introduced by substantial inorganic pools and transfers. The relative importance of organic and inorganic pools in supplying phosphorus to plants is largely unknown. Less is known about the other macro- and micro-

nutrients, but generally these nutrients are not particularly limiting in ecosystem function.

How Good Are Our Models?

In the last part of the meeting, three scientists presented models they are working on and with, providing a focus for discussion. The models are at different levels of aggregation and vary in their approach from a highly aggregated ecosystem model, based on the mechanisms and kinetics of plant growth, to a model of vegetation dynamics. The ecosystem model presented by E. B. Rastetter (The Ecosystems Center, Marine Biology Laboratory) invokes carbon:nitrogen interactions and kinetics to drive and control plant growth. Another model presented by S. B. Running (University of Montana) also is highly aggregated but is designed to take advantage of the opportunities now available to use the information obtained from satellite measurements as the driving variables (Running and Coughlan 1988). This model depends strongly on estimates of leaf area index (LAI), which can be used as a surrogate for energy interception and hence for calculation of biomass productivity. A model of vegetation dynamics presented by M. A. Huston (Oak Ridge National Laboratory) depends on (assumed) mechanisms of competition, with growth rates specified by empirical relationships derived from measurements on isolated trees (Huston et al. 1988). This model is being steadily improved by the introduction of mechanisms such as water balance and calculations of rates of nitrogen input to the systems based on litter decomposition (e.g., Pastor and Post 1986).

The discussion sessions based on the models led to considerable argument about the calibration, validation, and testing of models. As we progress toward larger and larger scales, such as landscapes and regions, the problems of model testing become more and more severe because of the difficulty of obtaining adequate data. Each system is unique, and conceptually models could be "tested" by complete specification of the characteristics of a system, at an appropriate level, with the model under test being run with the resulting parameter values over a series of appropriate time intervals. This is not possible.

The approach that emerged as the best of the available options was to use nested, hierarchical or cascaded models. It is possible to test models written at lower levels of organization much more rigorously than those written at higher—or more aggregated—levels. If we have confidence in the lower level, more detailed models, we can use them to evaluate the outputs and results from more aggregated models. Examples to illustrate this are the calculation of energy interception and photosynthesis by stands. Detailed models are available for these purposes. Aggregated models, making estimates of energy interception, and hence productivity, for landscapes may use relatively coarse approximations for these processes. The results can be checked and refined by the more detailed models. The same procedure can be used for various aspects of hydrologic models. Integration of ecosystem- and landscape-level models with global-level models was not dealt with in any detail at the meeting, but the need for such integration was recognized.

Where to from Here?

The workshop reached the conclusion that, in terms of the theoretical knowledge and empirical information needed to paramaterize stand-level models and to establish confidence in their use as predictive and analytical tools, we can currently deal reasonably well with water, less well with nutrients, and not well with carbon. Thus considerable research is needed on various aspects of the carbon cycle, a number of issues related to nutrients, and on some specific areas of the hydrologic cycle.

The goal of closure should remain part of the objectives of any major project, since closed system models must embody the constraints and requirements for biological and physical consistency that guarantee the results from such models are, at least, within reasonable bounds.

Heterogeneity of stands remains a significant problem. Most models are written on the assumption that the spatial area of concern is homogeneous in its properties, so that calculations relating to some (hypothetical) representative area provide a reasonable idea of what is happening over larger or smaller areas. This may not be the case, and the question of how to deal with heterogeneity at all levels requires considerable attention. Scaling up the output from a small-area model to represent a landscape is not just a matter of running the model with different parameter values to account for the range of conditions in the various landscape units; there are feedbacks and interactions at higher organizational levels that may not be present at lower levels. An example of such feedback is the matter of LAI noted in relation to one of the models discussed earlier. If LAI can be estimated from satellite measurements and used to estimate biomass production, there must be some means of accounting for feedbacks at the carbon allocation level: what happens to the biomass produced—does it contribute to greater foliage mass, is it allocated to other organs or processes. . .or. . .? Feedbacks and interactions are critical elements of ecosystem models that require additional attention in scaling up.

Finally, there was consensus to recommend the development of a major proposal or proposals for large-scale, widespread experiments associated with concurrent model development and (as far as possible) testing. The research could encompass a range of environments, but at least at one site comparisons should be made among both nested and similar-scale models, in an effort to reduce unnecessary proliferation of individual models being developed, often for similar purposes. There must be some move toward a series of optimum models for different purposes, partly to test the adequacy of models, partly to push toward the simplest adequate model set, and partly for economy of research effort. The proposals should include scales large enough to address

the utility of satellite technology, as satellites provide the only feasible method of taking measurements that represent significant portions of the earth's surface, and scales small enough to include processes relevant to individual trees.

Preliminary discussions have begun at the Rocky Mountain Forest and Range Experiment Station and with representatives from several granting agencies regarding the wisdom of and interest in conducting a large-scale experiment on forest ecosystem model comparison and improvement. Scientists involved in the workshop and additional scientists doing closely related work will be polled for their interest in such a program. If the level of interest expressed at the workshop and in the several months following is an indication, a preliminary planning effort will be undertaken.

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Keywords: Carbon cycle, nutrient cycle, hydrologic cycle, forest ecosystem model, closure, closed system model, workshop

U.S. Department of Agriculture
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Rocky Mountain Forest and Range Experiment Station

Rocky Mountains

Southwest

Great Plains

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

RESEARCH FOCUS

Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

RESEARCH LOCATIONS

Research Work Units of the Rocky Mountain Station are operated in cooperation with universities in the following cities:

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Fort Collins, Colorado*
Laramie, Wyoming
Lincoln, Nebraska
Rapid City, South Dakota
Tempe, Arizona

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